

Stratospheric Aerosol and Gas Experiment (SAGE) III Data Validation Plan



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1. INTRODUCTION

The Stratospheric Aerosol and Gas Experiment III (SAGE III) is an important part of NASA's Earth Observing System (EOS Science Plan, 1999; EOS Reference Handbook, 1999) to help provide a better understanding the effects of natural and human-induced changes on the global environment. SAGE III provides limb occultation measurements with a flexible instrument design that permits on orbit reprogramming and channel selection with up to 800 channels spanning the ultraviolet, visible, and near infrared (280-1040 nm). Solar observations will provide high resolution vertical profiles of multi-wavelength aerosol extinction, the molecular density of ozone, nitrogen dioxide, and water vapor, as well as profiles of temperature, pressure, and cloud presence. In addition, the inclusion of a repositionable solar attenuator will allow lunar occultation observations that will improve geographic coverage and permit measurements of nitrogen trioxide and chlorine dioxide in addition to ozone and nitrogen dioxide.

1.1 Purpose and Scope

This Validation Plan outlines an approach to verify the SAGE III measurement and retrieval algorithm system and a strategy to acquire correlative measurements in order to validate the accuracy and precision of the SAGE III Standard Science Products. The plan covers the first 2 years of operation of the SAGE III/Meteor-3M mission commencing with expected launch of the SAGE III instrument in December 2001. A second SAGE III instrument will be placed on the International Space Station (ISS) in 2005. Validation plans for the ISS/SAGE III instrument will be included in a future revision of this document.

The original SAGE III Validation Plan was first submitted in 1997 and has been revised as plans to obtain correlative measurements have changed due to launch delays of the Meteor-3M mission. The most significant setback in the design of these plans resulted from missed correlative measurement opportunities during the SAGE III Ozone Loss and Validation Experiment (SOLVE) in the winter of 1999-2000, which was partially designed to support the validation of SAGE III and other satellite instruments. Although this campaign provided a rich data set for indirect comparisons, the SOLVE-2 field campaign is designed to fulfill the original goal of providing direct correlative measurement observations for SAGE III validation and is planned for January-February 2003.

1.2 Applicable Documents

1.2.1 Controlling Documents

1999 EOS Reference Handbook; A Guide to NASA's Earth Science Enterprise and the Earth Observing System, EOS Project Science Office, Code 900, NASA/GSFC, NP-1999-08-134-GSFC, 1999.

1.2.2 SAGE III ATBD Documents

SAGE III Algorithm Theoretical Basis Document: Transmission Data Products, LaRC 475-00-108, February 2000.

SAGE III Algorithm Theoretical Basis Document: Temperature and Pressure Data Products, LaRC 475-00-104, February 2000.

SAGE III Algorithm Theoretical Basis Document: Aerosol Data Products, LaRC 475-00-105, February 2000.

SAGE III Algorithm Theoretical Basis Document: Nitrogen Dioxide Data Products, LaRC 475-00-101, February 2000.

SAGE III Algorithm Theoretical Basis Document: Nitrogen Trioxide Data Products, LaRC 475-00-102, February 2000.

SAGE III Algorithm Theoretical Basis Document: Chlorine Dioxide Data Products, LaRC 475-00-103, February 2000.

SAGE III Algorithm Theoretical Basis Document: Water Vapor Data Products, LaRC 475-00-100, February 2000.

SAGE III Algorithm Theoretical Basis Document: Cloud Presence Data Products, LaRC 475-00-106, February 2000.

SAGE III Algorithm Theoretical Basis Document: Ozone Data Products, LaRC 475-00-107, February 2000.

1.3 Configuration Control

The SAGE III Validation Plan is maintained by the SAGE III Science Computing Facility (SCF) and managed under the SAGE III SCF Software Configuration Management Plan, LaRC 475-03-120. The approved version of the SAGE III Validation Document will be available at URL: <http://eospsso.gsfc.nasa.gov/validation/sageval.html>

1.4 Revision History

The original version of this document was dated July 15, 1997. Version 2.0 was released on April 1, 1999. Version 3.0 was dated April 24, 2000. This release, Version 4.0 is date November 17, 2001.

2. MISSION OVERVIEW

2.1 Science Objectives

Atmospheric ozone is an important greenhouse gas present in both the troposphere and stratosphere. It shields the Earth's environment from harmful ultraviolet radiation, but also acts as a major oxidizing species and can affect the lifetimes of many chemical species in the atmosphere. Ozone also absorbs and emits radiation in several wavelength ranges and plays a prominent role in the radiative balance of the climate. A principal goal of the SAGE III experiment is to accurately and precisely determine spatial and temporal distributions of ozone and some of those species (NO_2 , NO_3 , and OCIO) that affect its distribution. Profile measurements by SAGE III will provide crucial information on long-term variations and trends, particularly around the tropopause where radiative forcing is sensitive to changes in ozone.

Atmospheric aerosols also influence the radiative balance of the Earth's climate, not only by affecting the amount of radiation absorbed and emitted, but also by altering the optical and physical properties of clouds. It is well known that the injection of volcanic aerosols into the stratosphere can cause significant radiative forcings that last a few years. However, it has only recently been recognized that volcanic aerosols can be linked with changes of stratospheric ozone and that these effects must be accounted for in ozone trend analysis. Lower in the atmosphere, enhanced aerosol levels in the troposphere may have a more profound radiative impact than those from

volcanic eruptions, especially as industrial activity increases in developing countries. SAGE III measurements can probe the upper troposphere and provide insight in a region where aerosol observations are scarce. These measurements will extend the ~20 year global aerosol record made by the SAGE family of instruments and provide valuable information on the aerosol distribution and their evolution.

SAGE III will also provide profile measurements on water vapor and clouds. Since water vapor is the principal greenhouse gas in the atmosphere, information on its vertical and horizontal distribution and trend is important for understanding its subtle influence on climate. The instrument will further provide multi-wavelength measurements of polar stratospheric clouds (PSCs) and sub-visible cirrus, which will be useful for understanding their distribution and how they may influence atmospheric chemistry, radiation, and dynamics.

In addition to constituent profiles, SAGE III will obtain temperature and pressure profiles. These measurements are needed to remove dependencies on external sources for this information and to improve the accuracy of the retrieved constituents. Temperature and pressure measurements will be valuable for interpreting SAGE III observations and for addressing outstanding scientific issues such as climate change.

In summary, the experimental objectives for the SAGE III mission are:

- Retrieve global profiles of atmospheric aerosol extinction, temperature, and pressure and molecular density profiles of ozone, water vapor, nitrogen dioxide, nitrogen trioxide, chlorine dioxide with 0.5 km vertical resolution;
- Determine long-term trends in aerosol extinction, gaseous species and temperature;
- Characterize tropospheric as well as stratospheric clouds and investigate their effects on the Earth's environment, including radiative, microphysical, and chemical interactions;
- Provide atmospheric data essential for the interpretation and calibration of other satellite sensors, including EOS instruments; and
- Investigate the spatial and temporal variability of these species in order to determine their role in climate processes, biogeochemical cycles, and the hydrological cycle.

2.2 Instrument Background

SAGE III provides limb occultation measurements with a flexible instrument design that permits on orbit reprogramming and channel selection of a charge coupled device (CCD) with up to 800 channels spanning the ultraviolet, visible, and near infrared (280-1040 nm). A single photodiode will add aerosol extinction measurements at 1550 nm. Solar observations will provide high resolution vertical profiles of multi-wavelength aerosol extinction, the molecular density of ozone, nitrogen dioxide, and water vapor, as well as profiles of temperature, pressure, and cloud presence. The inclusion of a repositionable solar attenuator will permit lunar occultation observations of nitrogen trioxide and chlorine dioxide, in addition to improved geographical coverage of O₃ and NO₂. For solar occultation events, the instrument has a 0.008° vertical field-of-view and a 0.025° horizontal field-of-view. For lunar occultation events, the instrument uses a horizontal field-of-view of 0.041°.

The fundamental aspect of the satellite experiment is the measurement of atmospheric transmission along the satellite-sun (or moon) line-of-sight (LOS) during each occultation event (see Fig. 1). As the sun or moon ascends or descends behind the Earth, the instrument scans continuously across the solar (or lunar) disk and multiple transmission measurements are made at each tangent altitude. Each measurement event takes about 2-4 minutes to complete. The irradiance measurements are normalized by those measurements made outside the atmosphere, from which a transmission profile is then constructed with a vertical resolution of about 1/2 km. The retrieval of

individual constituents depends upon the separation of the relative absorption and scattering contributions of atmospheric species at different wavelengths. A basic assumption of the algorithm retrieval is that the atmosphere is horizontally homogeneous within a 1/2 km layer on scales of at least 200 km. For many situations, this is probably a good assumption for most stratospheric constituents, but is not always true for cloud and may well be a poor approximation for other constituents in the troposphere. Details on the algorithm retrieval are provided in the Algorithm Theoretical Basis Documents (ATBD), which are available at the URL: <http://eosps0.gsfc.nasa.gov/atbd/sagetables.html>.

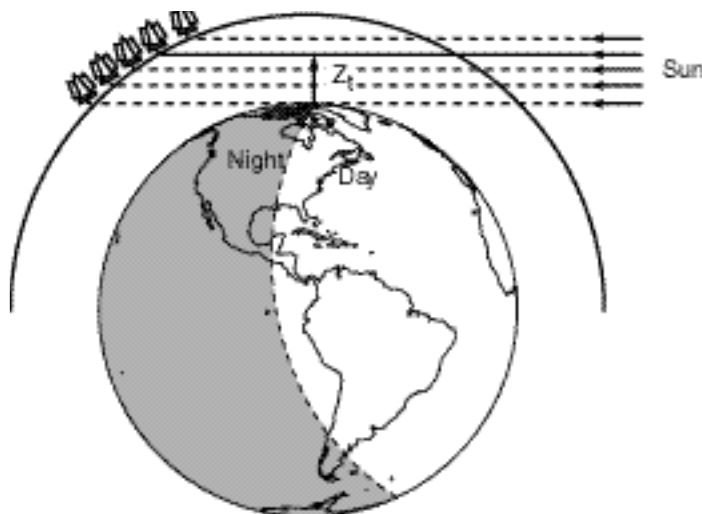


Figure 1. A sunset occultation event as viewed by the satellite. The instrument scans the solar disk at the tangent height (Z_t) and follows it until the sun is obscured. Different layers of the atmosphere are successively sampled during the event (see McCormick et al. (1979) for a general overview of solar occultation technique).

2.3 Launch Dates and Orbit Coverage

The SAGE III experiment consists of two missions designed to acquire global coverage over a multi-year period: launch on board a Russian Meteor-3M spacecraft is scheduled for December 2001 and integration of an instrument on board the International Space Station in 2005. For high latitude coverage, the Meteor-3M spacecraft will be placed into a polar, sun-synchronous orbit at an altitude of approximately 1020 km and inclination of 99.5°. The spacecraft will have a nominal equatorial crossing of 9:15 am, with an expected lifetime of at least 3 years. Low and mid latitudinal coverage will be provided principally by a SAGE III instrument mounted on the International Space Station (ISS). The ISS orbit will be inclined at 51.6° at an altitude of ~350 km.

The nominal time-latitude coverage of local satellite occultation events for the SAGE III/Meteor-3M missions is displayed in Fig. 2. For this mission, satellite sunrise events will occur between ~35° S and ~60° S, while sunset events will take place between ~50° N and ~80° N. Lunar events will vary from pole-to-pole. Note that the motion of the sun at the surface, however, may differ from that experienced by the satellite (e.g. a sunrise may occur to an observer at the surface during a satellite sunset event). A list of predicted SAGE III solar and lunar measurement locations covering a period of 6 months will be provided on the SAGE III homepage (<http://www-sage3.larc.nasa.gov>) and updated each quarter to facilitate the acquisition of correlative measurements for SAGE III data comparisons.

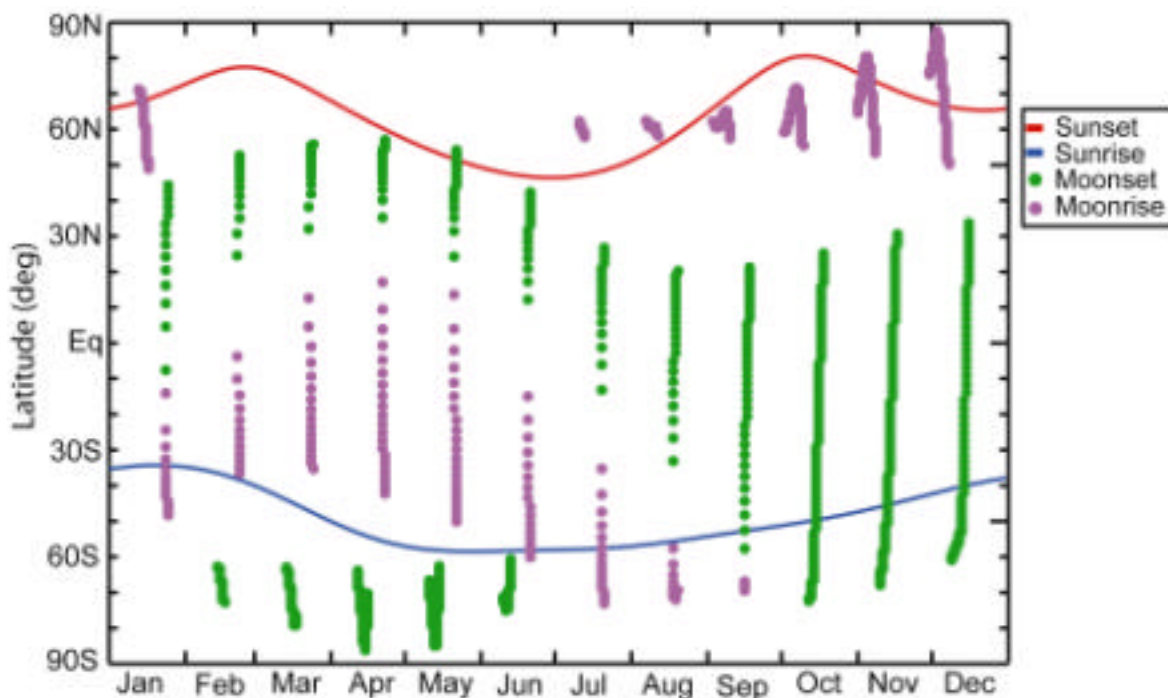


Figure 2. Nominal SAGE III/Meteor-3M time-latitude measurement coverage for 2002.

2.4 Science Data Products

Table 1 lists the Level 1B and 2 Standard Science Products to be produced for each occultation event opportunity, assuming penetration of the signal through the particular layer of the atmosphere. The anticipated accuracy, precision, profile range, and vertical resolution are also provided for each product. Vertical profiles will extend upwards from the boundary-layer or cloud top, whichever is higher. These products will be available at the NASA Langley Research Center (LaRC) Distributed Active Archive Center (DAAC) approximately 3 months after commencement of instrument operation. Real-time data products will also be available at the SAGE III homepage (<http://www-sage3.larc.nasa.gov/sage3>). In addition to the Standard Science Products, a number of related Research Science Products such as aerosol surface area and mass will be produced and evaluated by the SAGE III Science Team before being distributed to the general science community. A strategy to validate a few of the Research Science Products is included in this plan.

Table 1. SAGE III Standard Science Products

Product Name	Expected Accuracy/Precision	Vertical Resolution/Range
Level-1 B Transmission profiles (< 80 wavelengths)	0.05%:0.05%	0.5 km:0-100 km
Aerosol extinction profiles and stratospheric optical depth (@ 8 wavelengths)	5%:5%	0.5 km:0-40 km
H ₂ O Concentration (altitude)	10%:15%	0.5 km: 0-50 km
NO ₂ Concentration (altitude)	10%:15%	0.5 km: 10-50 km
Slant path column amt.		0.5 km: 10-50 km
NO ₃ (lunar only) Concentration (altitude)	10%:10%	1 km: 20-55 km
O ₃ Concentration (Altitude)	6%:5%	0.5 km: 6-85 km
Slant path column amt.		0.5 km: 50-85 km
OCIO (lunar only) Concentration (altitude)	25%:20%	1 km: 15-25 km
Pressure	2%:2%	0.5 km: 0-85 km
Temperature (altitude)	2 K:2 K	0.5 km: 0-85 km
Cloud presence	N/A	0.5 km: 6-30 km

3. VALIDATION OVERVIEW

3.1 Approach

The SAGE III validation program will be based upon an analysis of the retrieval algorithm and comparisons using SAGE III instrument and engineering data and external correlative measurements. The retrieval algorithm analysis will include an evaluation of the soundness of the retrieval process through a comparison of results from a forward model with those from the inverse retrieval algorithm. This effort will permit consistency checks along major milestones of the retrieval process and will allow it to be evaluated under different simulated atmospheric conditions. Another effort will center upon a self-consistency analysis of different retrieval techniques for the same parameter; (e.g., determination of aerosol extinction using the method utilized by SAGE I/II (Chu and McCormick, 1979) and a multiple linear regression technique identified in the ATBD. The large number of radiance measurements available from different CCD channels will also permit inversion retrievals to be performed using combinations of different radiance channels. Not only will this activity provide insight into the robustness of the selected retrieval method, it will provide information on the instrument performance and retrieval error propagation. Self-consistency analysis will be performed when appropriate such as between solar and lunar occultation events when these events occur at similar latitudes.

External measurement comparisons with SAGE III will be conducted with independent correlative measurements of sufficient number and of known quality to validate the expected accuracy of the SAGE III Standard and Research Science Products. The use of correlative measurements requires knowledge of their accuracy and precision. It further requires an understanding of how inter-comparisons should be performed as well as knowledge of the representation of their sampling. The term validation implies a level of agreement between independently measured quantities. Agreement is understood when estimates of uncertainty (error bars) between measurements overlap, even though absolute magnitudes may differ by substantial amounts. In a rigorous sense, validation requires that correlative measurements are traceable to accepted measurement standards; however, such standards do not exist for many of the SAGE III measurements. For these cases, validation will be based upon intercomparisons between different measurement techniques to gain confidence on the relative level of accuracy of the SAGE III data products.

An estimate of the precision of the SAGE III measurements will be determined by comparing the observed measurement variance to an independent estimate of the geophysical variance (Cunnold et al., 1984). For SAGE and SAGE II, this technique was employed at low latitudes where planetary and synoptic scale wave disturbances are relatively weak. Since SAGE III/Meteor-3M solar measurements are restricted to mid and high latitudes, an estimate of the measurement precision will be conducted, instead, during the summer months when variations from planetary wave activity should be relatively weak in the lower stratosphere. A science team member will lead the validation of each SAGE III Standard Science Product. Major findings from these validation studies will be reported in the scientific literature.

The acquisition of correlative measurements will be patterned after the successful SAM II, SAGE I/II, and UARS validation programs (e.g., Russell et al., 1981; Russell and McCormick, 1989; Gille et al., 1996). In situ and remote sensors on the ground, aircraft, balloons, and satellites will obtain correlative data. Efforts will be made to understand the representativeness of the measurements and minimize differences in time and space between SAGE III and correlative measurements. The program is designed to leverage upon low risk, operational measurement activities and to supplement these measurements with airborne and balloon campaigns tailored to specific sampling needs. In addition to these efforts, internal instrument data (e.g. mirror reflectivity, CCD quantum efficiency, spectrometer temperature) will provide crucial information on the performance of the sensor needed to adequately perform validation activities.

3.2 Correlative Measurement Sampling Requirements

The sampling needs of the SAGE III validation program are driven by the limb occultation geometry and include, but are not limited to the following:

- obtain vertical profile measurements for each Standard Science Product
- ensure long-term and low risk correlative measurement program with stable and well-characterized instruments over the lifetime of the project
- minimize uncertainties associated with each spatial and temporal coincidence between SAGE III events and correlative measurement opportunities
- examine the inhomogeneity along the line-of-sight, especially in the presence of subvisible cirrus and polar stratospheric clouds
- conduct correlative measurements under different atmospheric conditions
- determine the altitude registration of the transmission profile (resolution < 100 meters)

3.3 Criteria for Coincidence

For correlative measurements to be useful for validation, they must reflect the atmospheric conditions observed by the SAGE III instrument. This places constraints on the allowable separation in time and space between satellite occultation events and correlative measurement opportunities. By arbitrarily setting small coincidence criteria for ground-based or balloon measurements, the number of correlative measurement opportunities is greatly diminished. This in turn leads to an increase in complexity planning and scheduling of resources and cost of conducting correlative measurements activities. Arbitrary large coincidence criteria, on the other hand, confound the usefulness of these measurements with potentially larger uncertainties in sampling representativeness.

As guidelines for SAGE III validation activities of stratospheric species, the following spatial coincidence criteria have been adopted from the Upper Atmospheric Research Satellite (UARS) correlative measurement program. As a desired target, the SAGE III measurement point should lie within a 250 km radius of the correlative measurement site. An acceptable coincidence is one where the SAGE III observation lies within 500 km of the site. For species whose lifetimes are longer than a few days, an acceptable criterion is to obtain both correlative and SAGE III observations within 6 hours of each other, with 3 hours being adopted as the most desirable goal. For the validation of SAGE III tropospheric species, coincident criteria need to be more stringent as constituent fields have more variability. Under these circumstances, it is probably unreasonable to quantify a coincidence criterion other than to express the need for near simultaneous measurements.

For many ground-based locations, this coincidence criteria is restrictive and will produce a small comparison database because of the low number of SAGE III occultation events available each day and operational constraints imposed on ground-based sensors such as inclement weather. An alternative and promising approach that would enhance statistics for the intercomparison of long-lived species is to link correlative measurements with SAGE III sampling opportunities using forward and backward isentropic trajectories. With this technique, an ensemble of air parcels could be initialized at either satellite or correlative measurement locations and then allowed to disperse using wind information from assimilated meteorological fields. Intersections between trajectories from different measurement platforms within established coincident criteria would form a comparison data set. From these data, Kolmogorov-Smirnov (KS) tests could determine the likelihood that the observed distributions arose from the same parent population (Gibbons, 1985). The KS test is similar to the more familiar Chi-squared test except that the maximum difference between cumulative Probability Density Functions (PDF) between two samples is used instead of the maximum difference between their PDFs. The KS statistic provides a more quantitative measure of the agreement between the correlative observations than either the Student's *T* test or ranked sum tests of means (Gibbons, 1985). A previous intercomparison study using this approach com-

puted trajectories for 10-day periods and employed coincidence criteria of ± 1 hour, 1° latitude, 10° longitude, and 20 K (Pierce et al., 1997). To aid this type of analysis, the SAGE III Science Team will have access to an archive of isentropic trajectories computed for each SAGE III occultation location.

3.4 Measures of Success

Validation experiments are conducted to evaluate the accuracy of the retrieved parameters derived from SAGE III algorithms with independent correlative measurements. For measurements with Gaussian PDFs, agreement is understood when error bars between different instrument measurements overlap, even though values may differ. For measurements with different PDFs, KS tests provide an assessment of their relative agreement.

It should be realized that validation of a parameter to the expected level of accuracy listed in Table 1 may be deferred until correlative measurement uncertainty associated with atmospheric conditions is reduced. For example, aerosol lidars are expected to provide key correlative measurement information for the validation of SAGE III aerosol extinction profiles in the lower stratosphere. A major source of error in the use of lidar measurements arises from uncertainties in molecular scattering. Under the near-background aerosol conditions present in the stratosphere in late 1999, these uncertainties can dominate over other systematic errors and hinder the validation of the aerosol extinction products to the required accuracy. For this situation, validation of these products may have to be deferred until a volcanic eruption enhances stratospheric aerosol loading with relatively higher aerosol-to-molecular optical scattering cross-sections.

4. PRE-LAUNCH ACTIVITIES

4.1 Forward/Inverse Model Development

A detailed software simulator of the SAGE III experiment is being developed to reproduce major aspects of the spaceborne experiment and verify the retrieval algorithm systems. The simulator is composed of a series of modules, each one being a physical model of either the instrument (e.g. CCD and photodiode characteristics, telescope optics), spacecraft (e.g. orbital elements, scanning mirror characteristics) or the ambient atmosphere (e.g. constituent distributions and spectral properties). The simulator performs a forward transformation from assumed atmospheric constituent profiles (including knowledge of their homogeneity along the LOS) into Level 0 radiometric scanned data. These results are then inverted with the SAGE III retrieval algorithms and their products compared with *a priori* constituent distributions. Use of the simulator also permits detailed inspection of the processing software by examining incremental aspects of the retrieval algorithm. For example, comparisons could be made between the forward and inverse model calculations of the LOS view geometry and tangent altitude, solar and lunar disk crossing time, and construction of the transmission profile. Elements of this validation activity have been successfully used in the analysis of the SAGE II and III retrieval algorithms, with the result being a series of refinements to their respective software processing systems.

Besides performing algorithm verification studies, the simulator will be used to better understand and quantify the effect that clouds have on the retrieval of constituents. Idealized cloud distributions will be simulated and inverted. Additional simulation studies will be performed by introducing inhomogeneities in atmospheric density, pressure, temperature, and trace gas species. Over the next year, airborne correlative measurements of clouds, aerosols, and gases from the SOLVE measurement campaign will be feed into the simulator to produce Level 0 radiance data that can be compared with the POAM III observations. It is hoped that through these types of activities problems associated with clouds in the algorithm retrieval may be identified and better understood.

4.2 Spectroscopy

A review of molecular absorption cross sections as it pertains to the SAGE III instrument is presented in Appendix D of the SAGE III ATBDs. The discussion in each appendix is focused on the specific details of the individual molecules measured by SAGE III. The discussion also includes information on the rest of the spectrum where absorption by that species could interfere with the retrieval of other molecules and identifies additional measurement requirements.

4.3 Correlative Measurement Studies

The SAGE III Ozone Loss and Validation Experiments (SOLVE) 2 campaign is a comprehensive satellite, airborne (NASA DC-8 aircraft), balloon, and ground-based measurement campaign designed to acquire SAGE III correlative measurements and to study processes responsible for lower stratospheric ozone loss at high latitudes during winter and early spring. The campaign will take place between January and February 2003. Details on the SOLVE-2 mission objectives, instrument payloads, participants, and measurement periods will be made following selection from a website available on the SAGE III project URL. The SOLVE-2 NASA Research Announcement is expected to be released in the fall of 2001.

Under the original field mission plan, SOLVE was partially designed to provide extensive correlative measurements needed to validate the accuracy of SAGE III measurements and understand many underlying assumptions in its retrieval algorithm. Unfortunately, a delay in the launch of the SAGE III/Meteor-3M satellite instrument until December 2001 prevented this opportunity for direct instrument intercomparisons. However, intercomparisons between operational research satellite instruments (e.g., SAGE II, HALOE, and POAM III) and the wide range of in situ and remote sensing instruments that took place during SOLVE permits an assessment of their relative biases, which can be transferred to SAGE III comparisons during SOLVE-2. .

5. POST-LAUNCH ACTIVITIES

5.1 Strategy and Priorities

The SAGE III correlative measurement strategy embraces a series of observational activities needed to satisfy the validation objectives listed above. It leverages upon ongoing ground-based measurement activities, with little risk and cost to the project. A few of these sites will be augmented with additional instrumentation by the project to ensure a minimum correlative measurement network. Concurrent satellite programs will also provide an important database for assessing biases and precision between spaceborne sensors (e.g. SAGE II and POAM III). It is expected that these satellite measurements will be supplemented by balloon and airborne flights to provide measurements not available by other observational networks.

Because resources are limited, priorities must be identified in order to provide an adequate database for validation. In view of the importance of determining ozone trends in the upper troposphere and lower stratosphere and the need for understanding the impact that aerosols and clouds have on ozone retrievals, this plan emphasizes the collection of correlative measurements required to validate ozone, water vapor, nitrogen dioxide and stratospheric aerosol measurements during the first 2 years of operation. It does, however, provide plans to acquire sufficient measurements to validate other SAGE III products, or at least, perform consistency checks on them.

5.2 Existing Operational Surface Networks

An important component of the SAGE III validation plan is the intercomparison of complementary observations by other measurement programs. This activity will permit ongoing intercomparisons to occur immediately following launch and to continue throughout the lifetime of the mission. Most of the stations participating in these networks have long measurement records and will be funded during the next 2-5 years. Coordination of correlative measurement opportunities from existing instrument networks with SAGE III measurement opportunities will be made through the SAGE III homepage (www-sage3.larc.nasa.gov) and through email notices.

Network for the Detection of Stratospheric Change (NDSC) The NDSC promises to play a central role in providing multi-year observations during the lifetime of each of the SAGE III instruments. Several sites have instrument suites that can provide profiles of most of the SAGE III measurement species. Careful instrument calibration and intercomparison procedures are followed at each site to ensure that small trends can be detected over multiple years (see <http://www.ndsc.ncep.noaa.gov>).

Because of their location and instrument complement, the NDSC primary sites at Lauder, NZ; Ny Alesund, Norway; Eureka, Canada; and Thule, Greenland have been identified by the SAGE III Science Team as *anchor* measurement sites for the SAGE III/Meteor-3M validation program. The measurement coverage displayed in Fig. 2 for this satellite shows that sunrise events will occur near the latitude of Lauder (~45° S) during November and March. For satellite sunset events, co-incident measurement opportunities will take place in late October/early November, February, March, and September near 70°N.

Table 2 lists measurement capabilities from these stations that are needed for SAGE III validation. It should be noted that other NDSC primary and secondary measurement sites also offer important correlative measurement capabilities for validation of SAGE III/Meteor-3M data products. The NDSC site at Table Mountain, CA, for example, offers the only ground-based measurement of NO₃ available for comparison with SAGE III lunar events.

It is critical that effective communication links are maintained with the NDSC to ensure that correlative measurement opportunities are identified and comparison activities are optimized between teams. Drs. P. McCormick and C. Trepte from the SAGE III Science Team have been granted membership on the NDSC Theoretical Investigation Team to enhance this coordination and have already established contacts with the different sites (more information on the NDSC can be found at <http://www.ndsc.ncep.noaa.gov/>).

Table2. Observations Available at Anchor Correlative Measurements Sites

NDSC Site	Measurements
Eureka, Canada (80.1° N, 86.4° W)	ozone, aerosol lidars FTIR (NO ₂ , HCl, ClNO ₃ , NO column) ECC ozonesondes
Ny Alesund, Norway (78.9° N, 11.9° E)	aerosol, ozone, and temperature lidars solar, lunar, and starlight photometers UV/Visible spectrometer (O ₃ , NO ₂ , BrO, OCIO) FTIR (NO ₂ , HCl, ClNO ₃ , NO column) microwave O ₃ , ClO ECC ozonesondes temperature, relative humidity sondes
Thule, Greenland (76.5° N, 68.8° W)	aerosol, temperature lidars UV/Visible spectrometer (O ₃ , NO ₂ , OCIO) FTIR measurements ECC ozonesondes
Lauder, New Zealand (45.05° S, 169.7° E)	aerosol lidars Umkehr ozone profiles UV/Visible spectrometer (O ₃ , NO ₂ , OCIO) FTIR measurements microwave O ₃ and H ₂ O

World Meteorological Ozonesonde Network Key ozone profile measurements from the WMO ozonesonde network are needed to validate SAGE III observations between about 8 km and 25 km (<http://www.tor.ec.gc.ca/woudc/>). Identifying and understanding changes in ozone in the lower stratosphere and upper troposphere is a primary measurement objective for the SAGE III satellite experiment. Many of the WMO stations used Electrochemical Concentration Cell (ECC) instruments, which are often calibrated against the accepted standard reference technique (ultraviolet photometer) to an accuracy of $\pm 5\%$ and a precision of 5%. Ozone profile measurements are routinely available from the WMO ozonesonde network, which is a confederation of measurement teams from participating nations. Most sites are located in the mid and high latitudes of the Northern hemisphere. Relatively few stations are located in the tropics and mid latitude regions of the Southern Hemisphere (WMO, 1991; Logan, 1999).

Since each nation is responsible for operating and distributing their measurements to the international community, the frequency of ozonesonde flights varies from about once a week to once a month at different stations. The SAGE III project will coordinate with different instrument teams to facilitate the launching of ozonesondes for sites identified as being within the sampling criterion for correlative measurement opportunities. These opportunities will be based upon forecast trajectories using NCEP forecast products. Approximately 50 supplemental ECC ozonesonde instruments will be provided to NDSC sites at Ny Alesund, Spitsbergen and at Lauder, NZ to ensure that a significant number of intercomparison opportunities will be available for comparison for the first year of operation. Trajectory tools will be employed to enhance the number of comparison opportunities. Using these tools, it is hoped that over 200 coincidences in the northern high latitudes will be available for comparison studies during the first year of operation.

WMO Radiosonde Network The international radiosonde network provides profiles of temperature, pressure (altitude), and relative humidity at stations dispersed around the globe. Measurements are typically made at 0 and 12 GMT. These measurements will be used in the validation of SAGE III temperature and pressure retrievals. Because observations are keyed to these specific periods, no attempt will be made to coordinate special correlative measurement activities with these sites. In the upper troposphere and lower stratosphere, the radiosonde temperature accuracy is reported to be about 2 K.

MOZAIC (Measurement of OZone by Airbus In-service AirCraft) program consists of automatic in situ measurements of ozone and water vapor by long range airliners flying all over the world. As such, they provide detailed ozone and water vapor at cruise altitude (~9-12 km), which can be used for validation studies and to enhance science studies. Dr. C. Trepte has submitted an application to the MOZAIC program coordinator seeking permission to access the database and support collaborative studies

International Aerosol Lidar Network A confederation of international lidar investigators make measurements of tropospheric and stratospheric aerosol. Some of these members are also members of the NDSC network. The SAGE III project will coordinate with different investigators to facilitate the collection of lidar profiles during periods identified as being within the sampling criterion for correlative measurement opportunities. These facilities will be especially useful following a recent volcanic eruption to help track the global dispersion of volcanic aerosol layers.

Russian Measurement Network. Aerosol, ozone, and nitrogen dioxide observations will be available from sites in Moscow (56° N), Murmansk (69° N), Tomsk (57° N), and a north Caucasus site (44° N). Measurement opportunities from these sites are being coordinated by the Russian members of the SAGE III Science Team.

Additional Ground-based and Balloon-borne Measurement Activities A number of additional facilities exist around the globe that are not associated with the organizations listed above, but can provide correlative measurement data of known quality. The Umkehr and Dobson ozone observational sites and the Atmospheric Radiation Measurement (ARM) field sites are examples of these activities. The SAGE III project will contact these programs as their plans materialize.

The coordination of SAGE III correlative measurements is also being conducted with international partners. Many countries support high altitude balloon instruments that have flight opportunities every year. For example, the BALLAD and RADIBAL are aerosol instruments supported by the Service d'Aeronomie du CNRS (SA) that routinely fly each year. If they are launched at suitable latitudes and periods, they can provide valuable information for the SAGE III/Meteor-3M validation program. Dr. C. Brogniez from University of Lille will be the primary contact for coordinating European correlative measurement opportunities. In addition to these activities, validation measurements in support of the Japanese ILAS-II, the Canadian ACE, and the European ENVISAT-1 satellite instruments will take place in 2002 and 2003 (see below). Drs. Chu, Thomason, and Trepte from the SAGE III Science Team are guest investigators on these different validation programs and will facilitate comparisons with SAGE III data.

5.3 Existing Satellite Data

Initial intercomparison studies will rely heavily upon the climatology of the constituent distributions and archived satellite data sets. These studies will be augmented with valuable intercomparisons during near measurement coincidences between SAGE III, SAGE II, and POAM III satellite occultation events. Comparison opportunities are greatest for POAM III, which is on SPOT 4 in a sun-synchronous orbit. Much fewer opportunities exist for SAGE II/SAGE III comparisons, in part, because of the different orbit inclination of SAGE II. A significant reduction in overlap opportunities also exists because of a SAGE II instrument problem that occurred in July 2000. These comparisons are critical for extending the long-term occultation record should provide one of the best assessments of relative measurement accuracy because of the similarity in instrument designs, measurement geometry, and the extensive correlative measurement comparison records available for each instrument.

Comparisons with other current satellite instruments are also planned and are listed in Table 3. This list is not intended to be comprehensive, but is meant to give a flavor for the breadth of satellite correlative measurement opportunities available. Comparisons between SAGE III; GOMOS, MIPAS, SCIAMACHY on the European ENVISAT satellite; the Canadian ACE satellite mission, and ILAS on the Japanese ADEOS II satellite should be especially valuable for valida-

tion studies. Trajectory tools will also be employed in comparison studies between satellite measurements to enhance the number of coincident measurement opportunities. Several members of the SAGE III Science Team are members on validation teams for these the two satellite platforms and will have access to and participate in discussion on their science and validation data sets.

Table 3. Concurrent Satellite Experiments with SAGE III/Meteor-3M

Satellite/ Observations	Period	Latitude Coverage
SAGE II (ERBS) • 1.02, .525, .452, & .385 μm aerosol extinction • O_3 , NO_2 , H_2O	October 1984 - present	80°N - 80°S (seasonally dependent)
SBUV 2 (NOAA polar orbiters) • O_3 conc.	1989 - 1994; 1996 - present	80°N - 80°S (sunlit portion)
GOME (ERS-2) • O_3 , OCIO, NO_2 , BrO	1995 - present	global
POAM III (SPOT 4) • 1.02, .922, .779, .442, & .353 μm aerosol extinction • O_3 , NO_2 , H_2O • temperature & pressure	April 1998 - present	Sunrise: 55°N -71°N Sunset: 63°S -88°S
ILAS II (ADEOS II) • .780, 7.16, 8.27 10.60 & 11.76 μm aerosol extinction • O_3 , NO_2 , H_2O • temperature and pressure	Launch: Fall 2002	Sunrise: 56°N -70°N Sunset: 63°S -88°S
GOMOS (ENVISAT) • aerosol extinction (IR to UV) • O_3 , H_2O , NO_2 , NO_3 , BrO, OCIO • temperature & pressure	Launch: February 2002	Global
MIPAS (ENVISAT) • aerosol extinction (IR) • O_3 , NO_2 , H_2O	Launch: February 2002	Global
SCIAMACHY (ENVISAT) • aerosol extinction (IR to UV) • O_3 , H_2O , NO_2 , NO_3 , OCIO temperature & pressure	Launch: February 2002	Nadir view: Global Limb view:
SABER (TIMED) • O_3 , H_2O • temperature	Launch: December 2001	Limb view: near Global
ACE • O_3 , H_2O , NO_2 , aerosol extinction	Launch: December 2002	Limb view

5.4 Airborne Measurement Activities

Although considerable progress can be made towards the validation of SAGE III data products through comparisons with other satellite missions and ground-based instrument networks, concurrent correlative measurements are still needed to assess many of the requirements identified in section 3.2.

The proposed **SAGE III Ozone Loss and Validation Experiment (SOLVE) II** is a DC-8 aircraft and small balloon measurement campaign that is designed to acquire correlative data needed to validate measurements from the SAGE III satellite mission. SOLVE-2 is an extension of the original campaign conducted in the Arctic during the 1999-2000 winter in which direct SAGE III inter-comparison activities were not accomplished because of a prolonged delay in the launch of the satellite instrument. This earlier mission had several detailed science objectives in addition to the satellite measurement validation goals. These process scale science objectives became the primary focus of the mission when the SAGE III launch was delayed, although SOLVE data are being used in conjunction with measurements from other satellite instruments for validation studies. SOLVE-2 is co-sponsored by the Upper Atmosphere Research Program (UARP), the Atmospheric Chemistry Modeling and Analysis Program (ACMAP) and Earth Observing System (EOS) of NASA's Earth Science Enterprise (ESE).

DC-8 aircraft flights will acquire correlative data at the tangent measurement locations for solar and lunar SAGE III occultation events under different meteorological settings. It is also envisioned that DC-8 underflights with other satellite missions such as POAM III, ENVISAT, or ADEOS II will also take place during the mission to aid intercomparison studies. The field campaign is scheduled to take place over a 3-4 week period between January 1, 2003 and February 15, 2003 and may operate from several sites such as Kiruna, Sweden; Fairbanks, Alaska; and one or more locations in mid latitudes.

An important aspect of the aircraft payload is obtaining vertical profile measurements to maximize the range of overlap with SAGE III profile data. This will also permit measurements to be obtained along the satellite sun (moon) slant path to gain better understanding on the impact that clouds or inhomogeneities in the constituent distributions may have on the retrieval. These measurements will also serve to verify the altitude registration of the SAGE III profile measurements.

The SOLVE-2 mission will also include profile measurements of ozone, water vapor, temperature, and aerosol size distribution from small balloons. These measurements will provide linkage to previous satellite validation activities and will provide a valuable cross reference to other long term records. A set of 6-8 balloon launches is also anticipated from Kiruna, Sweden, which will be at approximately the same latitude of measurement for SAGE III sunset occultation events during the campaign.

5.5 Validation Strategy by Species

Aerosols

SAGE III aerosol extinction measurements will be validated by using comparisons with other satellite extinction measurements and derived observations from a variety of instruments (e.g. Russell et al., 1981). Comparisons between SAGE II and SAGE III will be particularly useful over all height ranges. Comparisons with POAM III, on the other hand, will be used primarily above 20 km. At lower heights, there are some unexplained differences between SAGE II and POAM III extinction (and other species) measurements that may reflect differences in the sensor design that are accentuated when atmospheric refraction effects become large. As a result, SAGE III validation will require additional aerosol measurements below 20 km to better understand these differences.

There are a large number of instruments that provide information on aerosol microphysical and optical properties. Lidar backscatter profile measurements have been used in previous measurement campaigns for the validation of SAM II, SAGE I, and SAGE II aerosol observations. Derivation of aerosol extinction from lidar data first requires application of a careful normalization procedure and extraction of the Rayleigh scattering contribution. Since Rayleigh scattering is derived from knowledge of atmospheric density (via temperature), large uncertainties in the lidar profiles can be introduced by uncertainties in the meteorological profile data. Best stratospheric lidar measurements can be obtained with contemporaneous temperature information. Conversion of

the lidar backscatter profiles to extinction profiles also requires knowledge of the aerosol backscatter-to-extinction coefficient. In the stratosphere, this factor is fairly well known, but can vary substantially in the troposphere depending upon the aerosol composition. For validation, it is desirable to have lidar measurements at multiple wavelengths to match the spectrum of measurements made by SAGE III. In addition, depolarization measurements are useful for discriminating between spherical and non-spherical particles.

Since SAGE III Science Products will be used to infer aerosol surface area, measurements of the aerosol size distribution from 0.01 - 5 μm will be needed for validation. It is believed that a combination of lidars, particle counters, and other instruments on aircraft and balloon platforms will be needed with satellite measurements for validation of the SAGE III aerosol products.

Ozone

Validation of SAGE III ozone concentration profiles will consist of comparisons with ground-based, balloon-borne, airborne and satellite measurements. Principal comparisons will focus on SAGE II, HALOE, MLS, and POAM III satellite measurements. These comparisons should permit an assessment of ozone concentration to an accuracy of <10% for most of the stratosphere. Ground-based microwave and lidar profile measurements at Ny, Alesund, Norway and Lauder, New Zealand will augment correlative satellite data in the upper stratosphere and mesosphere. In the lower stratosphere and upper troposphere, satellite measurements typically have larger uncertainties than at higher altitudes and SAGE III validation will be based upon comparisons with ECC ozonesondes and aircraft measurements.

Measurements are needed to assess the horizontal and vertical variability of stratospheric ozone over the slant path from aircraft flight altitude to at least 50 km. Measurements should have a vertical resolution of at least 1/2 km and horizontal resolution of 10 km. This requirement can be partially achieved with a zenith-viewing DIAL lidar system on the DC-8 tuned for stratospheric ozone concentrations. Contemporaneous measurements from an airborne chemiluminescence instrument are also desired to tie the lidar observations to the flight level. For higher altitudes, a combination of ground-based lidar and microwave measurements will be needed. These measurements also need to be compared with UV photometer measurements during coincident balloon flights to maintain traceability to the standard reference technique. It is especially important to acquire correlative measurements during both solar and lunar events and also at high and low latitudes where ozone distributions in the stratosphere and troposphere are considerably different.

Water Vapor

Although water vapor measurements in the upper troposphere and lower stratosphere have been conducted since the late 1940s, considerable disagreement remains between different techniques. Initial comparisons will be based upon SAGE III and POAM III measurement coincidences. In addition to these comparisons, it is desirable to have contemporaneous correlative measurements take place with a variety of water vapor sensors (e.g., frost point hygrometers, lidar, etc.) to bracket the range of uncertainty among each technique. Because of the highly variable nature of water vapor, measurements are needed along the LOS, especially in the upper troposphere where variations are expected to be significant. Airborne lidar systems have sufficient horizontal resolution, accuracy and precision to satisfy this objective.

Nitrogen Dioxide

Validation of SAGE III measurements of NO_2 is inherently difficult because it is rapidly photolyzed during local sunrise and quickly regenerated through reactions of NO with O_3 and ClO during local sunset. For instance, changes in the abundance of NO_2 can occur by a factor of 2-3 with a variation of the solar zenith angle from 85° to 90°. This rapid change in NO_2 concentration can introduce significant inhomogeneities along the SAGE III slant path that must be accounted for in order to retrieve an accurate value of NO_2 concentration. Corrections for this effect will require:

1. an accurate model description of the variation of NO_2 at sunrise and sunset

2. validation of the model with in situ measurements of the diurnal variation of NO₂ under varying conditions, and
3. verification of this method of correction by comparison with coincident in situ measurements, preferably during sunrise and sunset.

Because the development and validation of this diurnal correction model is external to the SAGE III measurement and algorithm retrieval system, no such correction is applied to the Standard Data Products. Application of the diurnal correction model to the satellite observations is essential, however, for comparisons with in situ measurements.

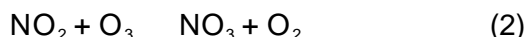
A more fruitful validation approach for SAGE III measurements of NO₂ will be based upon comparisons of the integrated slant path abundances, which will eliminate the need for the diurnal correction. This will include comparisons between near coincident observations by SAGE III and SAGE II (sunset events only), POAM III. Additional measurement opportunities will be available following the launch of ENVISAT and ADEOS II. Balloon observations (e.g., Mark IV instrument) can also provide valuable correlative measurement information; however, these measurements are infrequent and can be complicated by different meteorological conditions.

Chlorine Dioxide

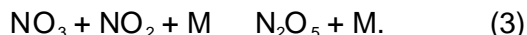
SAGE III OCIO observations are a new measurement for the SAGE instrument family and will be performed at night with lunar occultation. OCIO is primarily produced in the winter polar vortex through reactions involving BrO and ClO. Correlative measurements of these species are, thus, needed at twilight and for a short period before sunrise or after sunset. Column correlative measurements are available from ground-based instruments from NDSC sites at Ny Alesund and Eureka. Spaceborne correlative measurements are currently available from the GOME satellite instrument and will be available from the SCIAMACHY satellite instrument in 2001.

Nitrogen Trioxide

NO₃ is formed predominantly via the reaction



with a minor production channel through the thermal decomposition of N₂O₅ and removed during the daytime by photolysis. Since the rate of reaction (2) is relatively slow at stratospheric temperatures, concentrations of NO₃ are negligible during daylight hours. At night removal of NO₃ is mainly limited to reaction with NO₂ to produce N₂O₅ via



In the lower stratosphere thermal decomposition is too slow to be significant, and the steady-state expression for NO₃ indicates that NO₃ abundance is most directly controlled by O₃, i.e.,

$$\text{NO}_3|_{\text{ss}} = k_8 \text{O}_3 / k_9 \text{M}. \quad (4)$$

At high latitudes, nighttime measurements of O₃ and temperature may, therefore, be sufficient to check the consistency of the SAGE III lunar NO₃ observations. A ground-based interferometer based at Table Mountain, CA and led by Dr. S. Sander of JPL will provide column NO₃ correlative measurements during satellite overpasses. Development of this instrument for SAGE III validation has been supported by the EOS Validation Program.

Temperature

SAGE III will make temperature profile measurements, a capability not realized by either of its predecessors or by POAM III. These measurements will provide a self-consistent measurement of Rayleigh scattering needed to reduce ozone, nitrogen dioxide, and aerosol uncertainties above 30 km. Temperature profiles also will aid in the interpretation of SAGE III data (e.g. PSC and ozone observations) and help delineate the altitude of the tropopause.

Sounding rockets and airborne lidar systems offer the most promising measurement set for the validation of temperature profiles above 30 km. In support of this effort, the SAGE III Validation Team will seek a set of rocketsonde measurements from launch ranges at either Andoya, Norway or Esrange, Sweden. Measurements will be coordinated with SAGE III overpasses. Airborne lidar temperature measurements are also desirable to reduce errors in coincident times and locations. An added advantage of some of these systems is their ability to obtain simultaneous measurements of ozone, aerosol and temperature; and thus, provide the essential data set to evaluate improvements of SAGE III temperature measurements on ozone and aerosol retrievals. Validation of temperature at lower altitudes will also be based on comparison between SAGE III and radiosonde measurements. The comparisons however, may suffer from differences in time and space coincidences due to the fixed launch times of the radiosondes.

Altitude Registration of Transmission Profiles

The accurate determination of the transmission profile is fundamental to the retrieval of all species. For SAGE I, altitude registration errors of about 200 - 400 m resulted in biases in ozone mixing ratio and other species (Wang et al., 1996). For SAGE III, an altitude registration uncertainty of 100 m is desired. An assessment of systematic altitude biases could be achieved by measuring the altitude of the top of an optically thick cloud deck that lies along the slant path. However, cloud features vary considerably over short distances, and a more robust assessment of these errors might be obtained by examining differences in the vertical structure of the measured species. This approach should be especially useful near the tropopause, where strong vertical gradients often exist in these constituent distributions. Airborne lidar measurements coincident along the SAGE III slant path have the necessary spatial resolution, accuracy, and precision to satisfy this objective. A self-consistency check of the SAGE III lunar transmission profile could be obtained during period of measurement overlap with the solar occultation events.

Cloud Detection

A new product derived from SAGE III aerosol extinction measurements is the ability to detect the presence of optically thin cloud along the LOS from background and aged volcanic aerosol distributions (Kent and McCormick, 1997). Cloud observations along the LOS, consequently, are needed from about 6 km upward to 30 km. This requirement is complicated by the inhomogeneous nature of the cloud, its relatively small structure size compared to the ~200 km path length of the solar ray path through the atmosphere, and the fairly rapid changes that take place within a cloud. To fully satisfy these requirements requires extensive resources beyond the capabilities of most aircraft measurement campaigns. However, considerable insight can be gained from limited observations over the stated altitude range with a vertical resolution of about 100 m and a horizontal resolution of a few hundred meters. An airborne aerosol lidar system with multiple wavelengths would be best suited for achieving these requirements. Radiometric measurements of the sun from within and through the top of the cloud are also needed to simulate the SAGE III measurement directly. It is also highly desirable to obtain concurrent in situ cloud measurements (i.e., ice-water content, particle size distribution, temperature, etc). Such measurements require multiple flight paths along the LOS at varying altitudes under different cloudiness scenarios.

6. IMPLEMENTATION

The SAGE III data validation effort will be conducted by the SAGE III Science Team, project engineers, mission operations and algorithm development personnel, and correlative measurement investigators. Members of the Science Team will be responsible for the validation of each Science Standard Product. Dr. Chip Trepte of NASA LaRC will serve as the primary point-of-contact for coordinating the correlative measurement activities.

Findings from these studies will be reviewed by the SAGE III Science and Algorithm Development Teams. During the first year of operation, revisions to the SAGE III software algorithm and production of the Science Data Products will take place as needed. Findings from the validation studies will be reported in the scientific literature.

The validation strategy outlined in this plan is subject to change as conditions warrant. The Science Team will review its status at each Science Team Meeting (or as needed) and make appropriate changes.

7. SUMMARY

A validation strategy for the SAGE III Standard Science Data Products has been developed that embraces two different approaches. The first approach will be directed toward the evaluation of the retrieval process through a comparison of results from a SAGE III forward model with those from the inverse retrieval algorithm. Additional activities will be based on self-consistency checks using internal instrument and engineering data.

The other approach focuses on the collection of independent correlative measurements to compare and verify the accuracy of SAGE III Standard Science Products. Primary comparisons will be based upon a large number of coincidences between satellite, ground-based, and balloon-borne correlative measurements. Comparison techniques employing isentropic trajectories will also be used to enhance the number of coincidences between satellite and correlative measurement sites. Although these activities will provide considerable insight into relative biases between instrument measurements, aircraft observations are still needed along the satellite-sun line-of-sight to assess fundamental assumptions in the retrieval algorithm.

These comparisons will be greatly enhanced with direct comparison measurements from the planned SOLVE-2 campaign, which is scheduled for January-February 2003. This campaign will consist of measurements from the DC-8 aircraft and small balloons operating from high latitude and mid latitude bases. Findings from comparison studies will be published in scientific journals.

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